POPULATION, NITROGEN, AND ROW POSITION EFFECTS ON STRIP INTERCROPPED CORN YIELD AND MOISTURE

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ABSTRACT

For commercial grain farms, recent availability of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] with the same herbicide tolerance, and survey-quality automated navigation systems for agricultural equipment reduce the operational cost of strip intercropping the two species. Field experiments were conducted in Northeast Iowa to determine the effects of strip intercropping on corn grain yield and moisture, and to identify interactions with row position, plant populations (58 000, 80 000, and 108 000 seeds ha^{-1}), and sidedressed N rates (0, 90, 130, and 160 kg N ha^{-1}). Four strips were each divided into three 260 m sections and in each strip populations were randomly assigned to sections. Nitrogen rate was randomly assigned within each section to subunits consisting of 3 adjacent rows such that each N rate appeared at each row position for each population. Rows were harvested individually and analyzed in adjacent 3-row triplets. In a dry year, 2006, sidedressing had no effect and the mid population was highest yielding. In the wet year, 2007, the zero N rate had reduced yield and moisture, and yield was highest for the highest population. Outside rows yielded more and were dryer, but row position did not interact with other treatments. We recommend that in strip-intercropped corn, population and N levels are applied uniformly across all rows and that N applications are split to allow for adaptation to the weather.

BIOGRAPHICAL SKETCH

Clay Thomas Mitchell was born April 10, 1973 in Waterloo, Iowa. He received the Bachelor of Science in Biomedical Engineering from Harvard University in 1999. He purchased farmland near the family homestead and in 2000 became the 5th generation to operate The Mitchell Farm, a corn/soybean farm, in Geneseo Township, Tama County, Iowa.

Becoming well known for the adoption and development of leading automation techniques in grain farming has serendipitously brought invitations to conferences in over a dozen countries, allowing Clay to glean technologies from the best grain producing regions of the world.

Believing that agronomy is more important than engineering in increasing farm productivity, Clay came to Cornell to learn the methods and tenets of agronomy.

For the farmers and scientists in the field.

ACKNOWLEDGMENTS

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I owe my deepest gratitude to the Saltonstall family and my advisors, Dr. William Cox and Dr. Harold van Es. Not only in this work, but in all of the studies I've conducted over the last years and in my relaying results to farmers around the world I have attempted to emulate the wisdom of both men.

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INTRODUCTION

Previous research on strip intercropping of corn and soybean shows a 20-26% increase in corn border rows (Lesoing and Francis, 1999). However, the previous research is impacted by two significant factors that may increase variability and reduce the mean corn border response. Firstly, distance between the species is prone to operator error. Whereas the width of inner rows is fixed by the distance of planter row units on their toolbar, the border represents a “guess row.” Distance between the corn and soybean rows affects the interaction and yield response (Rees, 1986). Secondly, where herbicides are the main means of weed control, either a small number of limited spectrum compatible herbicides could be applied to both crops, or each crop could be treated individually. Because herbicide spray does not have a distinct edge, it would necessarily be the case for incompatible herbicides that either a reduced rate would reach the border, or small amounts of drift would impact the adjacent species (Kleijn and Snoeijing, 1997; Olszyk et al., 2004). Glyphosate-tolerant corn and soybeans and automated machine navigation are recent technologies that eliminate the concerns, and have not previously been used in strip intercropping studies.

Optimum plant density for corn has increased steadily over the past 70 years (Tokatlidis and Koutroubas, 2004). Previous studies have shown no interaction between plant population and nitrogen fertility in corn (Blumenthal et al., 2003; Subedi and Smith, 2006). However, barrenness, which is associated with high plant populations, increases under N stress and has been reported as high as 6% (Boomsma and Vyn, 2006) and 15% (Subedi and Smith, 2006). In strip-intercropped corn, response to extra population and nitrogen has been reported as high as 1250 kg/ha (West and Griffith, 1992).

Complete colinearity of field operations is becoming more common due to real-time kinematics (RTK) global positioning system (GPS) autosteering and its coupling with strip-tillage, as well as with niche practices like controlled-traffic farming, strip-intercropping, and raised bed farming. In these aligned farming systems the operations might be identical to a conventional system in every regard except simply the direction of operation, and yet a drastically different cropping environment is created by changing relative proximity of applied inputs, elimination of compaction, sunlight arbitrage, and improved surface water flow.

In addition to the step increases in resource use efficiency enabled by aligned farming systems, they offer powerful forensic evidence of the quality of the farming operation and the cost of deviation from target rates. Whereas in randomly trafficked fields, nonuniformity across the width of equipment becomes pixilated through sequential operations, in aligned farming systems systematic errors remain unobfuscated. Consequences of uneven residue spread at harvest, nonuniformly performing planter row units, and imperfect application of fertilizer and pesticides, are essentially digitized into discrete and easily measurable row-by-row variations.

The objective of this study was to find the effects of strip intercropping on corn grain yield and moisture, and to identify interactions with row position, plant populations, and sidedressed N rates.

MATERIALS AND METHODS

Site Description

A field-scale study was conducted on The Mitchell Farm (42°15´ N lat, 92°20´ W long) in northeast Iowa in 2006 and 2007 on a rainfed site that had been strip-intercropped to glyphosate[*N*-(phosphonomethyl)glycine]-tolerant corn and soybean since 2004. In 2003 the field was cropped with corn, concluding a long-term monocropped corn-soybean rotation which is typical of cash grain farms in Iowa. The site has a total elevation change of 24 m, with 80% of the area classified as moderately eroded Dinsdale silty clay loam (fine-silty, mixed, superactive, mesic Typic Argiudolls) on 2 to 5 percent slopes, 13% Tama silty clay loam (fine-silty, mixed, superactive mesic Typic Argiudolls) on 2 to 5 percent slopes, and 7% Nevin silty clay loam (fine-silty, mixed, superactive, mesic Aquic Pachic Argiudolls) on 0 to 2 percent slopes. Soil tests from 2007 showed an average pH of 6.5, a cation exchange capacity (CEC) of 12.8 meq/100g , and organic matter (OM) content of 3%.

Intercropping protocol at the site has twelve rows of corn (76 cm between rows) and 22 rows of soybean (38 cm between rows) with 3 m tramlines planted in a north–south orientation in 9-m-wide strips 780 m in length which are rotated annually. Soybean is no-till planted between corn stubble of the previous crop. Corn is planted into narrow tilled zones created from banding fall fertilizer to a depth of 20 cm. Distance between the corn and soybean strips is 57 cm. Controlled-traffic practices are followed with a specialized equipment set on exclusively 3 m track widths, which limits compaction to permanent traffic lanes between corn rows 4-5 and 8-9.

In 2007 soil samples were collected within each row of each subplot by mixing cores taken to a 15 cm depth at 5 m intervals, requiring over 7000 cores for 142 aggregated row samples. In order to achieve the sampling scale and consistency requirements, a prototype-the-go soil sampler (Agrobotics AutoProbe) was used, which comprises a standard hollow tube type soil probe within a single agricultural track, pulled by a small tractor. Samples were analyzed by A&L Analytical Laboratories (Memphis) using an inductively coupled plasma (ICP) instrument and Mehlich-3 extraction.

Experimental Design

The experiment was arranged with four replications of the main treatment population (58 000, 80 000, and 108 000 seeds ha^{-1}) allocated in a spatially-balanced experimental design (van Es et al., 2007a) by dividing four strips into 260 m sections and randomly assigning populations within the strips to a spatially-balanced subplot layout. Four N rates (0, 90, 130, and 160 kg N ha^{-1}) were nested within each main plot population treatment by randomly assigning each N rate to sets of 3 adjacent rows that we call “triplets,” and which therefore occur at four positions within the strip. Each N rate appeared at each row position for each population. ‘Pioneer 33B49,’ a 112-day glyphosate tolerant hybrid was planted May 1 in 2006 and May 8 in 2007. Soybean strips were planted 7-10 days after corn strips.

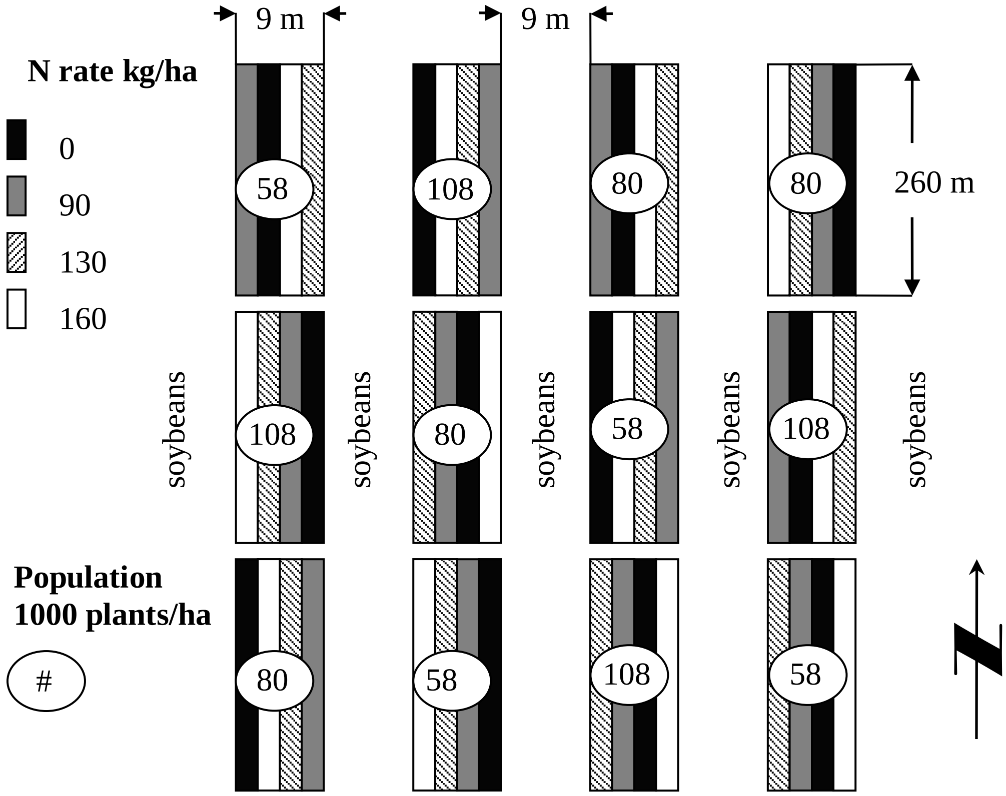

Figure 1. Plot layout of the experiment for the 2006 season.

In November of 2005 and 2006, a blend of granular $(NH_4)_2HPO$ (18-46-0) and K_2O (0-0-60) was injected into the soybean stubble at nutrient rates of 115 kg P ha^{-1} and 140 kg K ha^{-1} respectively. Corn stubble rotating to soybean received no additional fertilizer.

In accordance with established production practices in this field, automatic guidance systems were used to achieve consistent distances between strips and precise placement of fertilizer relative to seed despite nonconsecutive field passes and a concomitant inapplicability of mechanical row markers. For fertilizer banding and planting operations, both the tractors and implements used tilt-compensated RTK GPS navigation units (i.e. the planter and fertilizer applicator have steering means and autosteering systems in addition to those on the tractors) for true hands-free sub-inch accuracy at the row units.

A sprayer with 18 m booms and 38 cm nozzle spacing was used for sidedressing and herbicide application from the soybean tramlines, covering half of each adjacent corn strip per pass. Excellent weed control with glyphosate at .8 kg a.e. ha^{-1} was achieved by application at emergence (VE) and again at the 5^{th} leaf stage (V5). At V8, urea-ammonium nitrate solution (28-0-0) was surface applied using drop-nozzles and zero-degree tips in order to stream the fertilizer at the base of the corn rows.

In 2007 wind speeds of over 100 km/h on both July 17 and July 22 caused severe mid-season lodging in the corn. Uniform gooseneck growth resulted in a prostrate lower plant and upright stature above the 6^{th} node, effectively shifting the corn strips eastward, with the eastern corn border rows growing above the western soybean border rows. Brace roots developed up to the 5^{th} node. On September 14 an unseasonal frost killed the corn as it was reaching zero milk line.

In 2006 harvest was conducted on October 28, and in 2007 on Nov 9. A small combine was equipped with an impact-style yield monitor and elevator-mounted moisture sensor, calibrated for low grain flow rates, and set to record at 1-sec intervals. Rows were individually harvested at an average speed of 6.9 km/hr, and individually unloaded into a weigh wagon, which provided a second measurement of yield. It follows that the combine path diverged from the tramlines that are followed by the class-8 combine under normal production, with 12 times as many passes conducted from the outside rows inward. Most consequentially, soybean adjacent to the plots had to be harvested before corn to clear a path for the combine to harvest the outside row. Because the 9 m platform header fits tightly between the corn strips, some harvest damage to the outside rows occurred in 2007 due to lodging.

Statistical Analysis

Consistent with the N treatment design, triplets were analyzed rather than individual rows, analogous to the split-plot design cited by Milliken and Johnson,

2009. Because the border effect on corn yields is beyond dispute, reducing some sensitivity to row position is traded off to gain sensitivity to population and N treatments in this arrangement. The analysis applied to the unbalanced, mixed effects model was restricted maximum likelihood (REML) method using JMP version 7 (SAS Inst., 2007). A full model was constructed containing the fixed effects shown in Table 2. The error term for the whole plots, swath (within year) by population is equivalent to "block" for consistency with Milliken & Johnson. The interactions with year were included because the two years represent weather patterns for which very different responses would be expected for our treatments, interactions were tested with year.

In 2006 swath 4 was substantially different due to an unknown management error. The REML analysis was conducted both including and omitting the aberrant swath with the only difference being that the estimates are shifted upwards and swath is no longer a significant source of variation when it is omitted.

Mean comparisons were inclusive of all data. For significant effects, pairwise comparisons of means were conducted for the highest-level interaction that included the treatment using Tukey’s HSD test (P=0.05).

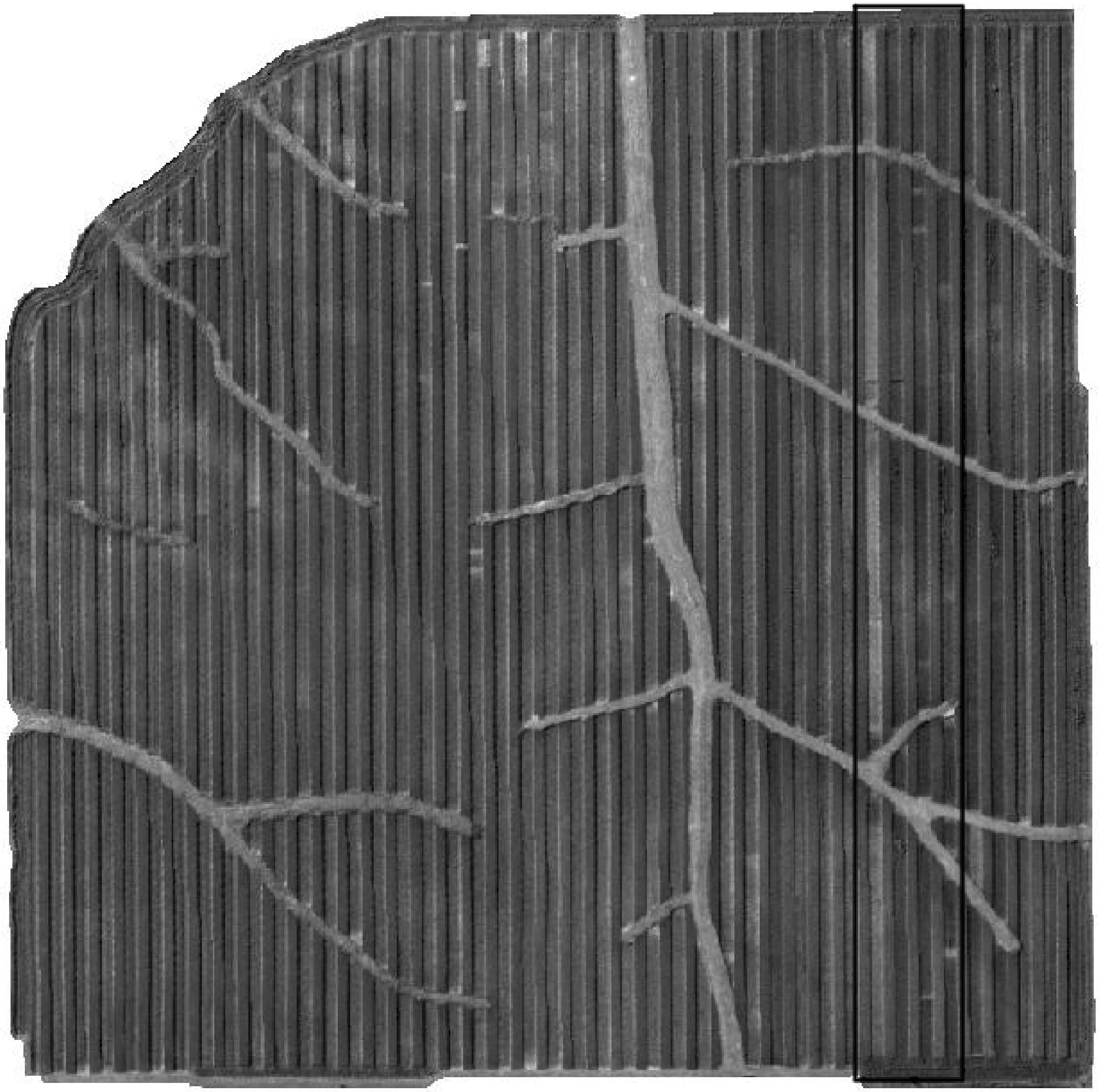

Figure 2. Aerial image from 2006 growing season. The superimposed black rectangle encloses the four swaths of the experiment. A clear difference can be seen on the westmost swath.

In order to reduce the opportunity for swath-wide management mistakes, extra swaths were planted in 2007 with efforts made in the plot layout to be consistent across the two years: when the corn and soybean strips were interchanged as per the usual rotation, the plots were shifted westward by 9 meters. Indeed, a broken tile line and planting errors required abandoning some subplots. However, a complete set of data was still collected, as there were sufficient usable plots to maintain four replications of each population. The effect of the adjusted plot layout was that by considering the swaths as blocks, the experiment became unbalanced.

However, because the systematic effects of machine field operations that are aligned with the plots result in unintended but systematic effects that overwhelm effects of native soil variations, there is no meaningful effect of swaths and subplots from year-to-year.

Alignment of all field operations increases systematic errors outside of our treatment responses and would be viewed as undesirable if we were working in a laboratory environment. However, the conditions and methods were chosen explicitly to represent a real-world production environment, and management errors are important sources of variation that are normally hidden.

In single-row harvesting, the samples are sufficiently long and close together to negate errors due to native soil variances. What we are left with is a pure measure of our treatment effects and management errors.

RESULTS AND DISCUSSION

The 2006 growing season had far below average rainfall until August and September, whereas 2007 had far above average cumulative rainfall (Table 1). Only in September did 2006 have more rainfall, when the monthly total was more than 2.5 times what was received in 2007. The 2007 season was much warmer, with higher monthly growing degree days (GDDs) in every month except July. The difference was greatest at the beginning and end of the season when 2007 had 30-40% more GDDs than 2006. The 2006 season can be characterized as dry with moderate temperature and 2007 as hot and wet.

Table 1. Monthly precipitation and growing degree days (GDD, 30-10 degree C) during 2006 and 2007 growing seasons and average from 1951 to 2010 at Grundy Center, IA.

	Precipitation			GDD		
Month	2006	2007	avg.	2006	2007	avg.
	-----------mm----------			--------degree C---------		
May	70	117	110	201	263	206
June	67	153	126	318	329	314
July	90	111	114	412	382	385
Aug.	150	309	106	366	402	353
Sept.	144	54	77	187	262	239
Total	521	745	533	1483	1638	1498

Contrasting seasonal weather resulted in highly divergent yield outcomes (Table 2). In 2006, yield averaged 10.9 Mg ha^{-1} and in 2007 averaged 8.8 Mg ha^{-1}. The yield of swath 4 in 2006 was 5.4 Mg ha^{-1} (Table 3). Because moisture continues to be dynamic after maturity and the recorded values represent the snapshot at harvest date, the late harvest dates resulted in grain moisture contents that were much nearer to equilibrium (Schmidt and Hallauer, 1966) than is typical for the region and therefore the differences between treatments were small (Table 4). Still, significant differences were found among treatments.

Population effect on yield had a significant interaction with year (Table 2) with the high population yielding lowest in the dry year, 2006, and the high population yielding most by an insignificant difference in the wet year, 2007 (Table 3). Sidedressed N rate had no effect in 2006, but there was a significantly lower yield and lower moisture at the zero N rate in 2007 (Tables 2 and 3). Yield had no interaction with population and N treatments.

Border effects were strong in both years for yield (Table 3) and moisture (Table 4). Yields were higher for outer rows by 25% in 2006 and 9% in 2007. In 2006, inside rows averaged 10.4 Mg ha^{-1} compared to 13.0 Mg ha^{-1} for outside rows. In 2007 inside rows averaged 8.6 Mg ha^{-1} compared to 9.4 for outside rows. The lower moisture for the outer rows augments the profitability slightly for the outer rows compared to the inner rows in addition to the yield effect by reducing grain drying costs.

Table 2. Fixed effects table for yield and grain moisture using REML.

Source	df	Yield F ratio exclusive†	Yield F ratio inclusive	Moisture F ratio exclusive	Moisture F ratio inclusive
Year	1	107.8***	3.9	50.4	14.6**
Population	2	1.3	2.6	0.3	2.2
Population*year	2	4.8*	7.5*	2.9	7.1*
Triplet	3	12.5***	5.7**	8.6***	9.6***
N	3	5.1**	4.1*	2.5	3.4*
Year*triplet	3	7.4***	2.3	4.5*	7.7***
Year*N	3	10.8***	7.2***	3.7*	3.9*
Triplet*population	6	1.5	0.5	1.0	0.9
Triplet*N	9	1.1	1.4	3.0	2.7*
Population*N	6	1.1	0.4	1.7	1.1
Year*population*N	6	2.7*	1.1	0.5	0.6

† Exclusive and inclusive are with regard to the swath 4 from 2006, which was aberrant.
* significant at the .05 level
** significant at the .01 level
*** significant at the .001 level

Higher populations are expected to have lower moisture even as yield increases (Widdicombe and Thelen, 2002), whereas variations in N supply are not expected to affect kernel drydown (Juki et al., 2007). The other interactions, those between treatments, were included because they have been suggested for investigation in previous literature, and meaningful interactions have been observed in other on-farm trials. In particular, it is expected that outside rows respond better to higher N rates and higher populations, and that higher populations require more N. The model was then reduced by removing interactions until only significant interactions remained (at a p-value of .05).

Table 3. Effects population and N rate, and row position on corn grain yield from 2006 to 2007.

Treatment		2006		2007	
		Mg ha^{-1}		Mg ha^{-1}	
Population (1000 plants ha^{-1})					
	58	11.13	AB	8.20	AB
	80	11.64	A	8.79	AB
	108	9.93	B	9.09	AB
N rate (kg ha^{-1})					
	0	11.06	AB	7.41	B
	90	10.67	AB	9.27	A
	130	11.00	AB	9.08	A
	160	10.87	AB	9.01	A
Triplet					
	rows 10-12	11.7	A	9	AB
	rows 1-3	11.2	AB	8.6	AB
	rows 4-6	10.4	B	8.6	AB
	rows 7-9	10.2	B	8.5	AB

† Means within row position, population or N rate followed by the same letter are not significantly different at P=.05 according to Tukey's HSD test.

Table 4. Effects of row position and N rate on moisture from 2006 to 2007.

Treatment		2006		2007	
		g kg^{-1}		g kg^{-1}	
Triplet					
	rows 1-3	176.6	A	160.6	C
	rows 4-6	175.7	AB	163.7	AB
	rows 7-9	175.6	AB	164.5	AB
	rows 10-12	173.6	BC	161.2	C
N rate (kg ha^{-1})					
	0	175.4	A	160.4	B
	90	175.6	A	163.0	A
	130	175.5	A	163.4	A
	160	174.9	A	163.2	A

† Means within row position or N rate followed by the same letter are not significantly different at P=.05 according to Tukey's HSD test.

Wheel traffic along one side of corn rows has been reported to significantly reduce yield in the absence of N fertilizer, but have no effect with adequate fertilization (Fausey and Dylla, 1984). However, four years of single-row harvesting on The Mitchell Farm has found no relationship between corn yield and traffic lane adjacency. Despite axle loads of over 30 tons and a dozen previous passes, soil physical properties in the wheel track are comparable to adjacent fields with annual tillage; most compaction is less than 15 cm deep and the most compacted layer is only 5 cm thick (Bolson and Kaleita, 2007).

Banded P and K fertilizer is likely to remain concentrated in the application zone for several years (Stecker et al., 2001; Yin and Vyn, 2002). The history of banding fertilizer on the site and errors associate with application are a large potential source of error.

CONCLUSION

While strip intercropping represents a viable way to increase corn yields through increases in border row yields, planting and N rates did not differ from monocropped corn, as there was no interaction of those treatments on row position. Furthermore, low planting rates (58,000 kernels ha^{-1}) yielded as well as the typical planting rate (80,000 kernels ha^{-1}), and the high planting rate (108,000 kernels ha^{-1}) actually reduced yield in the dry 2006 growing season. Border rows yielded more and had no interaction with population or N rates so no row-specific management practice had to be employed to achieve the yield benefit. In addition, border rows also had lower grain harvest moistures, which is a benefit because of less drying costs. In contrast, the yield gains from the 90 kg ha^{-1} sidedressed N rate in 2007 was accompanied by a 0.3% increase in moisture content, slightly muting the profit. The response of corn to the 90 kg ha^{-1} sidedressed N in the wet 2007 growing season but not the 2006 dry growing season is consistent with previously reported results (Sogbedji et al., 2001).

Much larger gains in yield in border rows are likely to be made from reducing management errors and misapplications than from fine-tuning plant populations and N rate from typical rates. Optimum N rates are strongly affected by seasonal weather and can be accounted for through adaptive management (Melkonian et al., 2007; van Es et al., 2007b). In corn systems where fertilizer is banded in the row, forensics for misapplication may be more easily conducted by row-by-row harvesting than extensive soil sampling (Appendix Table 1).

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APPENDIX

Table A1. Correlation coefficients for 2007 soil measurements (n=142).

	pH	P	K	Ca	Mg	S	Na	Zn	Mn	Fe	Cu	B
OM	0.19*	-0.41***	0.01	0.13	0.35***	0.43***	-0.4***	-0.08	-0.14	-0.18*	.51***	-0.07
pH		-0.11	-0.1	0.31***	0.24**	-0.01	-0.06	0.16	0.31***	-0.11	0.15	0.26**
Phosphorus			0.49***	0.12	-0.29***	0.63***	0.41***	0.22**	0.49***	0.61***	0.46***	0.22**
Potassium				0.23**	0.27**	0.04	0.12	0.16	0.21*	0.33***	0.16	0.03
Calcium					0.63***	0.19*	0.27**	0.11	0.55***	0.53***	0.14	0.14
Magnesium						-0.27**	-0.17*	0.08	-0.06	-0.1	-0.19*	0.01
Sulfur							0.48***	0.17*	0.41***	0.56***	0.34***	0.34***
Sodium								0.18*	0.44***	0.5***	0.51***	0.28***
Zinc									0.14	0.17*	0.24**	0.04
Manganese										0.72***	0.54***	0.35***
Iron											0.39***	0.14
Copper												0.46***

Table A2. Means and CVs for selected soil chemical properties from 2007 intrarow sampling (n=142).

	OM	pH	P	K	Ca	Mg	S	Na	Zn	Mn	Fe	Cu	B
mean	3.0	6.5	28.3	187.1	2051.1	406.3	11.0	21.0	4.1	66.3	117.7	2.0	0.7
CV	14.6	4.4	36.7	17.5	10.0	9.8	33.1	23.8	72.5	20.5	16.7	29.1	26.7

† OM is percentage, pH is cologarithm of the activity of dissolved hydrogen ions (H^+), and nutrients are concentrations.

Table A3. Yield and moisture by treatment for 2006 and 2007.

year	swath	section	row	population	Nitrogen	Moisture	yield
2006	1	m	1	108	130	18.2	17.23
2006	1	m	2	108	130	17.7	12.07
2006	1	m	3	108	130	18.5	11.49
2006	1	m	4	108	160	18.1	10.92
2006	1	m	5	108	160	18	9.77
2006	1	m	6	108	160	17.9	10.92
2006	1	m	7	108	0	18.4	7.47
2006	1	m	8	108	0	17.9	14.93
2006	1	m	9	108	0	17.8	10.92
2006	1	m	10	108	90	18	12.07
2006	1	m	11	108	90	17.7	14.36
2006	1	m	12	108	90	17.2	17.23
2006	1	n	1	80	0	17.9	13.79
2006	1	n	2	80	0	18.4	13.79
2006	1	n	3	80	0	18.9	12.64
2006	1	n	4	80	90	18.2	13.79
2006	1	n	5	80	90	18.5	11.49
2006	1	n	6	80	90	18.4	10.92
2006	1	n	7	80	130	18.7	7.47
2006	1	n	8	80	130	18.2	13.21
2006	1	n	9	80	130	18	13.21
2006	1	n	10	80	160	18.3	12.07
2006	1	n	11	80	160	18.1	12.64
2006	1	n	12	80	160	17.5	14.93
2006	1	s	1	58	160	17.4	14.93
2006	1	s	2	58	160	18	13.79
2006	1	s	3	58	160	17.8	13.21
2006	1	s	4	58	0	18.1	12.64
2006	1	s	5	58	0	17.8	14.93
2006	1	s	6	58	0	17.8	12.64
2006	1	s	7	58	90	18.4	8.62
2006	1	s	8	58	90	17.7	10.92
2006	1	s	9	58	90	17.6	14.56
2006	1	s	10	58	130	18	14.80
2006	1	s	11	58	130	17.8	12.64
2006	1	s	12	58	130	17	15.51
2006	2	m	1	58	90	16.9	13.55
2006	2	m	2	58	90	17.8	11.19
2006	2	m	3	58	90	18.1	10.61
2006	2	m	4	58	130	17.2	12.96
2006	2	m	5	58	130	17.5	12.96
2006	2	m	6	58	130	17.7	11.19

2006	2	m	7	58	160	17.8	8.84
2006	2	m	8	58	160	17.5	12.96
2006	2	m	9	58	160	17.4	14.73
2006	2	m	10	58	0	17.7	13.55
2006	2	m	11	58	0	18	11.78
2006	2	m	12	58	0	16.6	12.96
2006	2	n	1	80	130	17.1	15.32
2006	2	n	2	80	130	17.6	14.14
2006	2	n	3	80	130	18.6	12.37
2006	2	n	4	80	160	18.1	14.14
2006	2	n	5	80	160	18	11.19
2006	2	n	6	80	160	18.1	11.78
2006	2	n	7	80	0	17.7	13.55
2006	2	n	8	80	0	17.8	13.55
2006	2	n	9	80	0	18	11.78
2006	2	n	10	80	90	17.7	12.96
2006	2	n	11	80	90	18.1	15.91
2006	2	n	12	80	90	17.5	17.68
2006	2	s	1	108	160	17.2	15.91
2006	2	s	2	108	160	18.2	9.43
2006	2	s	3	108	160	18.4	9.43
2006	2	s	4	108	0	17.3	12.96
2006	2	s	5	108	0	18	10.61
2006	2	s	6	108	0	17.6	11.78
2006	2	s	7	108	90	17.9	10.02
2006	2	s	8	108	90	17.8	7.66
2006	2	s	9	108	90	17.7	10.02
2006	2	s	10	108	130	18	11.19
2006	2	s	11	108	130	18	10.02
2006	2	s	12	108	130	17.8	8.84
2006	3	m	1	80	160	17.2	16.38
2006	3	m	2	80	160	17.6	12.87
2006	3	m	3	80	160	18.1	12.28
2006	3	m	4	80	0	17.7	13.45
2006	3	m	5	80	0	17.5	13.45
2006	3	m	6	80	0	17.4	12.87
2006	3	m	7	80	90	17.8	11.70
2006	3	m	8	80	90	17.7	14.04
2006	3	m	9	80	90	17.5	12.28
2006	3	m	10	80	130	18	11.70
2006	3	m	11	80	130	17.3	15.21
2006	3	m	12	80	130	16.7	18.14
2006	3	n	1	108	90	17.8	15.79
2006	3	n	2	108	90	18.3	15.21
2006	3	n	3	108	90	18.5	9.94

2006	3	n	4	108	130	18	12.28
2006	3	n	5	108	130	18.2	10.53
2006	3	n	6	108	130	17.9	9.94
2006	3	n	7	108	160	18.1	12.28
2006	3	n	8	108	160	17.8	11.11
2006	3	n	9	108	160	17.7	10.53
2006	3	n	10	108	0	18.6	11.11
2006	3	n	11	108	0	18	12.28
2006	3	n	12	108	0	17.1	15.79
2006	3	s	1	58	0	17.4	15.21
2006	3	s	2	58	0	17.7	9.94
2006	3	s	3	58	0	18.2	13.45
2006	3	s	4	58	90	17.7	10.53
2006	3	s	5	58	90	17.8	11.70
2006	3	s	6	58	90	17.9	12.87
2006	3	s	7	58	130	18.1	11.11
2006	3	s	8	58	130	17.6	9.94
2006	3	s	9	58	130	17.6	12.28
2006	3	s	10	58	160	17.9	11.70
2006	3	s	11	58	160	17.7	14.04
2006	3	s	12	58	160	16.4	14.62
2006	4	m	1	108	0	16.7	6.97
2006	4	m	2	108	0	16.7	2.91
2006	4	m	3	108	0	17	5.81
2006	4	m	4	108	90	16.5	4.07
2006	4	m	5	108	90	16.6	5.23
2006	4	m	6	108	90	16.7	4.07
2006	4	m	7	108	130	16.7	5.81
2006	4	m	8	108	130	16.5	5.23
2006	4	m	9	108	130	16.5	6.97
2006	4	m	10	108	160	16.6	5.81
2006	4	m	11	108	160	16.6	4.07
2006	4	m	12	108	160	16.2	8.71
2006	4	n	1	58	130	16.7	7.55
2006	4	n	2	58	130	17	8.14
2006	4	n	3	58	130	17.1	8.14
2006	4	n	4	58	160	16.2	8.71
2006	4	n	5	58	160	17	4.65
2006	4	n	6	58	160	16.8	6.97
2006	4	n	7	58	0	16.9	9.88
2006	4	n	8	58	0	16.6	10.46
2006	4	n	9	58	0	16.6	4.65
2006	4	n	10	58	90	16.1	8.71
2006	4	n	11	58	90	16.6	8.71
2006	4	n	12	58	90	16.4	6.97

2006	4	s	1	80	90	16.5	7.55
2006	4	s	2	80	90	17.1	8.14
2006	4	s	3	80	90	17.3	3.48
2006	4	s	4	80	130	16.7	9.88
2006	4	s	5	80	130	16.6	8.71
2006	4	s	6	80	130	17	8.14
2006	4	s	7	80	160	17	8.14
2006	4	s	8	80	160	16.6	9.30
2006	4	s	9	80	160	16.4	7.55
2006	4	s	10	80	0	16.7	7.55
2006	4	s	11	80	0	16.5	6.97
2006	4	s	12	80	0	16.5	9.88
2007	2	m	1	58	160	15.8	8.29
2007	2	m	2	58	160	16.1	7.79
2007	2	m	3	58	160	16.5	8.24
2007	2	m	4	58	0	16	7.84
2007	2	m	5	58	0	15.8	5.82
2007	2	m	6	58	0	16.2	6.26
2007	2	m	7	58	90	16.3	8.49
2007	2	m	8	58	90	16.2	10.38
2007	2	m	9	58	90	16.3	8.24
2007	2	m	10	58	130	16.2	8.98
2007	2	m	11	58	130	16.1	9.00
2007	2	m	12	58	130	15.7	8.31
2007	2	s	1	80	90	15.6	9.26
2007	2	s	2	80	90	15.4	7.81
2007	2	s	3	80	90	15.9	9.40
2007	2	s	4	80	130	15.4	7.39
2007	2	s	5	80	130	15.7	6.79
2007	2	s	6	80	130	15.6	7.01
2007	2	s	7	80	160	16.2	8.85
2007	2	s	8	80	160	15.7	8.46
2007	2	s	9	80	160	16	8.97
2007	2	s	10	80	0	17.4	8.95
2007	2	s	11	80	0	15.8	8.29
2007	2	s	12	80	0	15.4	7.96
2007	3	n	1	80	130	16.8	9.73
2007	3	n	2	80	130	17	9.04
2007	3	n	3	80	130	17.3	9.75
2007	3	n	4	80	160	17.4	9.98
2007	3	n	5	80	160	18	9.53
2007	3	n	6	80	160	17.3	8.10
2007	3	n	7	80	0	17.1	7.72
2007	3	n	8	80	0	16.7	6.02
2007	3	n	9	80	0	16.6	6.18

2007	3	n	10	80	90	16.9	9.52
2007	3	n	11	80	90	16.7	9.22
2007	3	n	12	80	90	16.4	10.75
2007	4	m	1	108	130	15.2	11.81
2007	4	m	2	108	130	15.5	9.63
2007	4	m	3	108	130	15.9	10.84
2007	4	m	4	108	160	16	10.75
2007	4	m	5	108	160	15.9	7.86
2007	4	m	6	108	160	15.8	8.81
2007	4	m	7	108	0	15.3	8.50
2007	4	m	8	108	0	15.1	7.31
2007	4	m	9	108	0	15.5	6.58
2007	4	m	10	108	90	15.7	8.20
2007	4	m	11	108	90	15.6	9.75
2007	4	m	12	108	90	15.3	11.42
2007	4	n	1	58	90	16.1	9.04
2007	4	n	2	58	90	16.2	7.22
2007	4	n	3	58	90	16.3	8.87
2007	4	n	4	58	130	16.5	8.64
2007	4	n	5	58	130	16.6	7.87
2007	4	n	6	58	130	17.1	7.67
2007	4	n	7	58	160	16.7	8.77
2007	4	n	8	58	160	16.6	8.39
2007	4	n	9	58	160	16.4	7.46
2007	4	n	10	58	0	16.2	6.84
2007	4	n	11	58	0	15.9	5.78
2007	4	n	12	58	0	16	5.54
2007	5	m	1	108	0	14.7	6.32
2007	5	m	2	108	0	14.6	4.28
2007	5	m	3	108	0	15.3	5.70
2007	5	m	4	108	90	15.7	9.27
2007	5	m	5	108	90	16.1	10.13
2007	5	m	6	108	90	16.2	8.75
2007	5	m	7	108	130	16.2	9.95
2007	5	m	8	108	130	16.2	9.68
2007	5	m	9	108	130	16.2	9.02
2007	5	m	10	108	160	16	8.60
2007	5	m	11	108	160	15.7	8.72
2007	5	m	12	108	160	15	11.68
2007	5	n	1	80	0	15.6	8.28
2007	5	n	2	80	0	15.7	6.49
2007	5	n	3	80	0	16.1	7.90
2007	5	n	4	80	90	16.4	10.58
2007	5	n	5	80	90	16.6	8.88
2007	5	n	6	80	90	16.7	10.63

2007	5	n	7	80	130	16.6	9.85
2007	5	n	8	80	130	16.4	8.22
2007	5	n	9	80	130	16.3	8.28
2007	5	n	10	80	160	16.2	9.76
2007	5	n	11	80	160	16	9.44
2007	5	n	12	80	160	15.9	11.20
2007	6	m	1	80	160	15.7	9.97
2007	6	m	2	80	160	15.5	9.82
2007	6	m	3	80	160	15.9	10.49
2007	6	m	4	80	0	15.6	9.76
2007	6	m	5	80	0	15.4	6.72
2007	6	m	6	80	0	15.5	8.81
2007	6	m	7	80	90	16.2	9.28
2007	6	m	8	80	90	16.1	11.27
2007	6	m	9	80	90	16.3	9.55
2007	6	m	10	80	130	15.8	8.72
2007	6	m	11	80	130	15.6	9.45
2007	6	m	12	80	130	15.4	9.63
2007	6	n	1	108	160	16	9.80
2007	6	n	2	108	160	16	9.17
2007	6	n	3	108	160	16.3	10.19
2007	6	n	4	108	0	15.9	9.27
2007	6	n	5	108	0	15.7	7.13
2007	6	n	6	108	0	15.9	8.42
2007	6	n	7	108	90	16.5	9.94
2007	6	n	8	108	90	16.3	8.58
2007	6	n	9	108	90	16.3	9.55
2007	6	n	10	108	130	16.1	10.26
2007	6	n	11	108	130	15.9	9.30
2007	6	n	12	108	130	15.7	11.70
2007	6	s	1	58	0	16.1	7.01
2007	6	s	2	58	0	16.2	7.03
2007	6	s	3	58	0	16.4	8.22
2007	6	s	4	58	90	17	10.12
2007	6	s	5	58	90	17	9.41
2007	6	s	6	58	90	17.2	10.66
2007	6	s	7	58	130	16.9	10.23
2007	6	s	8	58	130	17.2	9.77
2007	6	s	9	58	130	18.2	8.11
2007	6	s	10	58	160	16.7	9.99
2007	6	s	11	58	160	16.7	7.60
2007	6	s	12	58	160	16.2	9.17
2007	7	m	1	108	90	16.1	10.90
2007	7	m	2	108	90	15.9	9.23
2007	7	m	3	108	90	16	10.64

2007	7	m	4	108	130	16.1	11.18
2007	7	m	5	108	130	16.3	11.66
2007	7	m	6	108	130	16.2	10.24
2007	7	m	7	108	160	16.4	7.23
2007	7	m	8	108	160	16.2	11.79
2007	7	m	9	108	160	16.3	9.91
2007	7	m	10	108	0	16.3	9.20
2007	7	m	11	108	0	16.4	9.53
2007	7	m	12	108	0	16.2	12.23
2007	7	n	1	58	130	16.9	9.74
2007	7	n	2	58	130	16.9	8.19
2007	7	n	3	58	130	16.7	8.51
2007	7	n	4	58	160	16.8	9.54
2007	7	n	5	58	160	16.9	7.85
2007	7	n	6	58	160	16.8	9.25
2007	7	n	7	58	0	17.1	7.29
2007	7	n	8	58	0	16.8	9.15
2007	7	n	9	58	0	16.8	8.27
2007	7	n	10	58	90	16.6	8.66
2007	7	n	11	58	90	16.4	8.85
2007	7	n	12	58	90	16.2	8.37

Table A4. Grain quality measurements for select rows 2006.

swath	row	sub	Protein	Oil	Starch	Moisture	%TN
1	1	s	8.1	3.4	60.3	19.5	1.458
1	1	m	8.4	3.5	59.9	20.2	1.465
1	1	n	8.4	3.2	60.4	18.8	1.41
1	2	s	7.7	3.4	60.6	19.6	1.361
1	2	m	7.8	3.4	60.8	19.5	1.324
1	2	n	8.2	3.3	60.3	19.3	1.413
1	5	s	7.8	3.4	60.6	20.2	1.421
1	5	m	8.5	3.5	60.1	19.8	1.461
1	5	n	8.1	3.4	60.4	19.1	1.465
2	1	s	7.2	3.3	61.4	18.8	1.284
2	1	m	8.1	3.3	60.9	18.4	1.481
2	1	n	7.5	3.4	60.9	19.2	1.342
2	2	s	7.8	3.3	60.6	19.8	1.279
2	2	m	8.3	3.4	60.2	19.1	1.48
2	2	n	7.7	3.3	60.7	19.7	1.45
2	5	s	7.6	3.4	60.8	19.8	1.289
2	5	m	8.2	3.5	60.2	19.5	1.383
2	5	n	7.8	3.3	60.8	19.7	1.232
3	1	s	8.3	3.3	60.3	19.8	1.395
3	1	m	7.9	3.3	60.9	18.6	1.352
3	1	n	8.7	3.3	59.9	19.1	1.52

3	2	s	8.2	3.6	59.8	20.1	1.294
3	2	m	7.6	3.4	60.9	18.8	1.302
3	2	n	8.2	3.3	60.4	19.0	1.444
3	5	s	7.9	3.3	60.4	20.2	1.367
3	5	m	7.9	3.3	60.7	19.6	1.291
3	5	n	8.4	3.3	60.2	19.7	1.36
4	1	s	7.3	3.3	61.4	18.8	1.246
4	1	m	7.1	3.4	61.8	18.6	1.122
4	1	n	7.3	3.4	61.5	18.8	1.118
4	2	s	6.6	3.3	62.0	18.7	1.049
4	2	m	6.6	3.2	62.0	18.9	1.098
4	2	n	6.7	3.2	61.7	19.6	1.034
4	5	s	6.5	3.3	62.1	18.5	1.134
4	5	m	6.6	3.3	62.1	19.0	1.055
4	5	n	6.7	3.3	61.8	19.2	1.12

Individual Plant Investigation

In order to gain insight into the causes of random row-by-row yield variations, an individual plant study was undertaken. The investigation was conducted in 2010 on a Wiota silt loam (fine-silty, mixed, superactive, mesic Pachic Argiudolls) of 1 percent southward slope at a Mitchell Farm paddock (42°15´ N lat, 92°22´ W long). The site has been in a corn-soybean rotation since 2002. In November of 2009, a blend of granular $(NH_4)_2HPO$ (18-46-0) and K_2O (0-0-60) was surface broadcast onto the soybean stubble at nutrient rates of 125 kg P ha^{-1} and 150 kg K ha^{-1} respectively. In December of 2009, anhydrous ammonia at a nutrient rate of 155 kg N ha^{-1} was injected at a row spacing of 76.2 cm with a 19-shank toolbar (Model 5300, Case IH, Racine, WI) at a heading of 260 degrees.

On April 13, 2011, corn was planted at a population of 81,500 seeds ha^{-1} in 76.2 cm rows at a heading of 245 degrees. Locations for 2 rectangular plots of 12 rows (9.144 m) by 4.572 m were randomly selected in each of two hybrids. Plots 1 and 4 were Pioneer 33T57 [Comparative Relative Maturity (CRM) of 113] and plots 2 and 3 were Pioneer 33W80 (CRM of 111). Both hybrids are rated for 1380 GDUs to silk.

The position of the nitrogen bands within each plot are given by the equations:

Plot 1 y =3.732x + (6.5 +294.5n)

Plot 2 y =3.732x + (170 +294.5n)

Plot 3 y =3.732x + (273 +294.5n)

Plot 4 y =3.732x + (227 +294.5n)

The nitrogen bands cross the corn rows every 294.5 cm (76.2 cm/sin15). In the 4 plots, 1240 plants emerged and were tagged at V2. Frost on May 9 resulted in widespread leaf necrosis, but did not reduce the plant population.

Measurements were taken to characterize each individual plant. Growth stage was recorded with a visual count along with a count of dead leaves on June 4. Growth stage was recorded again on June 16. Stalk diameter was measured by hand-caliper on June 25. Chlorophyll was measured on July 1 with a SPAD meter (Soil-Plant Analysis Development, Konica Minolta Holding, Inc., Tokyo, Japan). The position of each plant was measured on August 20 and again during harvest. Harvest was done October 4, 6, and 7th with each ear being individually weighed and photographed.

The effect of unevenness on yield was visualized using GS+ (Gamma Design Software, Plainwell, MI). Unevenness is defined as 100*(distance from A - distance from B)/(distance from A + distance from B) where A and B are the adjacent plants. Yields at identical coordinates were averaged. Autocorrelation analysis for yield was calculated with an active lag distance of 41.73 and uniform lag class interval of 2.78. Krigging included a minimum of 1 neighbor and maximum of 16 neighbors.

Along each axis of the plant yield map is the distance from each neighboring plant. Points closer to the origin are a higher local population and points further from the origin are lower population. The diagonal lines connecting the same number on each axis are isolines for population. The midpoint between the axis is perfect spacing and the "unevenness" increases with proximity to one axis or the other. The map shows that there was a big cost to skips, but not too much effect from unevenness unless it was extreme– a double or close to it. Also, the effect of being extremely uneven was only meaningful at very high populations.

The plant spacing signature, a JMP bubble plot, is used to show the distribution of plant spacings. Viewing the plant spacing signature in relationship to the plant yield map indicates that the field was planted at a suboptimal population, but that few plants were planted with sufficient unevenness to reduce yield. The sparse distribution of plants at extreme spacings in the plant signature also explains the nodal artifacts and asymmetries in extreme regions of the plant yield map.

In order to examine systematic row effects, an analysis of variance tested response to measured plant characteristics. In plot 1, chlorophyll was significantly different among rows. In plot 2, yield was significantly different among rows. In plot 3, stalk diameter was significantly different among rows. In plot 4, both chlorophyll and stalk diameter were significantly different among rows.

After taking differences of plant spacing into account, analysis of covariance showed that plot 1 had no significant differences for the 4 responses. In plot 2, yield was significantly different among rows. In plot 3, stalk diameter and yield were significantly different among rows. In plot 4, both chlorophyll and stalk diameter were significantly different among rows.

Testing for the relationship between plant unevenness and plant yield showed a significant linear correlation only for plots 2 and 3 with $r = -.13$ and $r = -.16$. Because plots 2 and 3 were a different hybrid from plots 1 and 4, the different response may be thus attributable. The linear correlation between plant population and yield was significant in all plots with higher yields at higher populations.

With a quadratic response surface model, plant population and unevenness explain 27 to 53% of yield variation.

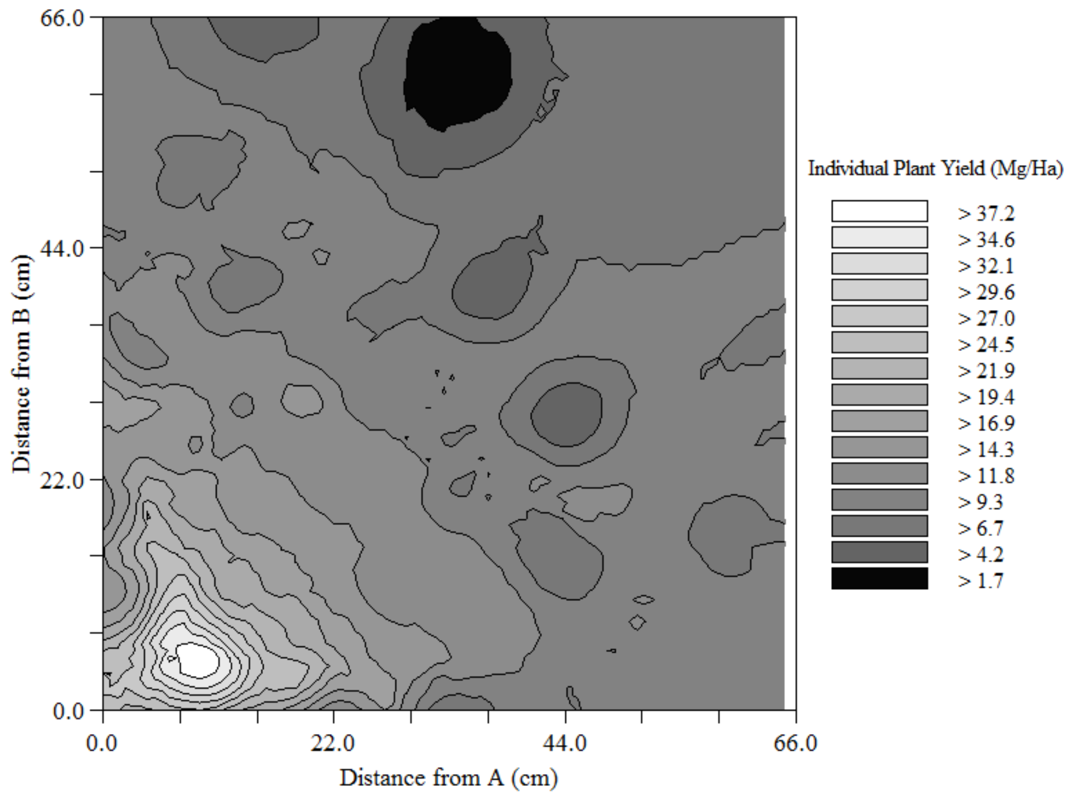

Figure A1. Plant spacing yield map for all plots.

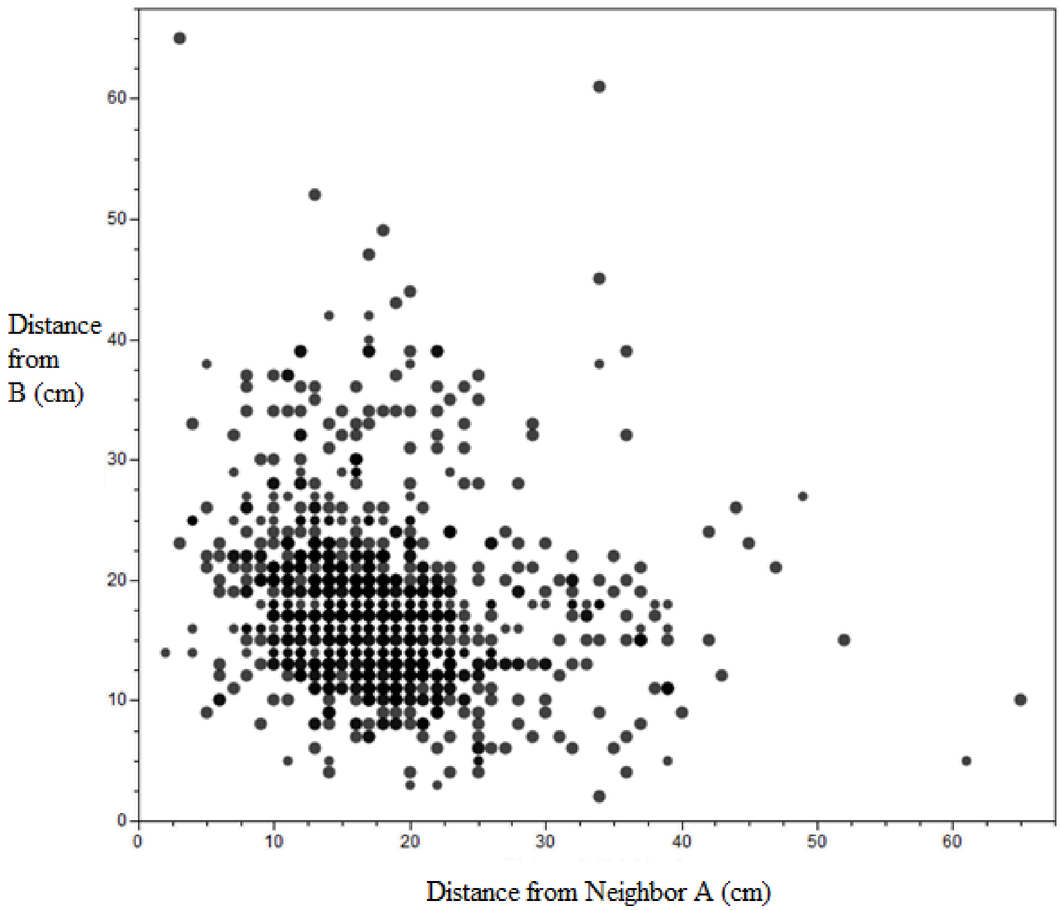

Figure A2. Plant spacing signature all plots.

Table A5. P-values for differences among rows.

plots	Response	p_value
1	Stalk diameter	0.161
2	Stalk diameter	0.717
3	Stalk diameter	0.016
4	Stalk diameter	0.001
1	Chlorophyl	0.025
2	Chlorophyl	0.381
3	Chlorophyl	0.381
4	Chlorophyl	0.000
1	Population	0.712
2	Population	0.710
3	Population	0.652
4	Population	0.887
1	Yield (bu/a)	0.778
2	Yield (bu/a)	0.010
3	Yield (bu/a)	0.648
4	Yield (bu/a)	0.975
1	Plant space (cm)	0.405
2	Plant space (cm)	0.491
3	Plant space (cm)	0.219
4	Plant space (cm)	0.901
1	Ear Grain Wt	0.601
2	Ear Grain Wt	0.890
3	Ear Grain Wt	0.283
4	Ear Grain Wt	0.807

Table A6. P-values for differences among rows after accounting for differences in spacing.

		p-value	
Plot	**Response**	**Row**	Covariate
1	Stalk diameter	0.144	0.381
2	Stalk diameter	0.573	0.002
3	Stalk diameter	0.040	0.001
4	Stalk diameter	0.001	0.026
1	Chlorophyl	0.443	0.508
2	Chlorophyl	0.364	0.176
3	Chlorophyl	0.286	0.023
4	Chlorophyl	0.001	0.058
1	Yield (bu/a)	0.290	0.001
2	Yield (bu/a)	0.001	0.001
3	Yield (bu/a)	0.004	0.001
4	Yield (bu/a)	0.164	0.001
1	Ear Grain Weight	0.623	0.626
2	Ear Grain Weight	0.904	0.074
3	Ear Grain Weight	0.397	0.236
4	Ear Grain Weight	0.841	0.532